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Advanced Liquid Oxygen (LO_2) Propellant Conditioning Concept Testing II

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TECHNICAL MEMORANDUM

ADVANCED LIQUID OXYGEN PROPELLANT CONDITIONING CONCEPT TESTING II

BACKGROUND

The requirements set for the pursuit of future heavy lift vehicles discussed in recent years include higher reliability, operability, and lower costs than current flight systems. As explored in a recent test program on propellant conditioning concepts, no-bleed propellant conditioning has been shown to offer advantages over active bleed systems such as in the space shuttle.[1]

The current shuttle system uses a high propellant bleed rate (6.0 lbm/s) to maintain cold oxidizer temperatures at the engine interface. The high bleed rate requires hardware such as valves, disconnects, and ducting. Maintaining this hardware is manpower intensive because of preflight maintenance and checkout requirements. These requirements can lead to increased onpad operations, failure hazards, alterations to flight schedules, and increased costs. Reducing or eliminating bleed requirements may help in improving the reliability, operability, and cost effectiveness of future launch vehicles. In addition, large amounts of propellant necessary for conditioning a high-bleed system will be reduced when incorporating either a passive recirculation or a low-bleed system.

Further work has been performed recently on LO_2 propellant conditioning, particularly no-bleed, between Marshall Space Flight Center (MSFC) and Martin Marietta Astronautics (MMA, now Lockheed Martin) under a NASA research announcement (NRA). The two-part NRA was a cooperative agreement to study operationally efficient feed systems. The first part of the NRA, which studied passive LO_2 propellant conditioning, was performed between July 1994 and January 1995. (The second part, cavitation prediction and prevention, is currently underway.[2]) The work done in part one was follow-on work to liquid oxygen propellant conditioning concept testing done between October 1992 and January 1994 at MSFC under a Joint Institutional Research and Development (JIRAD) program between MSFC and General Dynamics Space Systems (GDSS, now Lockheed Martin).[1]

The vehicle concept used for part one of the NRA was the National Launch System (NLS); however, the parameters studied address generic heavy lift vehicle concepts that have been studied in recent years as shown by figure 1. As defined by the JIRAD work, the no-bleed concept consists of an outer flow conditioning loop with two main feedlines connected by a main recirculation line. These feedlines are subjected to heat loads from the ambient environment. The downcomer feedline of the main recirculation loop is insulated more than the upcomer, allowing thermal gradients. These gradients promote natural recirculation in the loop, and thus cold propellant flows continuously out of the tank and through the feedlines. At the same time, the propellant absorbs heat and recirculates back to the tank. Removing the heat provides subcooling in the main feedlines for meeting pump operation requirements.

Unlike in the main feedlines, the flow in the engine feed ducts is not recirculated to the propellant tank. The fluid in the duct is, therefore, subjected to heat loads from the engine and ambient environment. The predominant heat transfer mechanism in an engine feed duct is through natural convection. The flow in the main recirculation loop causes shear instabilities to develop in the engine feed duct. These instabilities subsequently cause a series of circulation cells that are believed to enhance heat transfer upward through the duct.[1]

Two full-scale feedline test articles were provided by Lockheed-Martin for testing. The articles, which simulated propellant engine feed ducts, had slopes of 15° and 0°, respectively. A section, which simulated heat input from a LO_2 turbopump, was attached to the bottom of each test article except during one test segment for which a true LO_2 turbopump was used. Figure 2 shows details of the test articles used for this project.

OBJECTIVES

The objectives of this expanded LO_2 conditioning work were to further anchor models on LO_2 conditioning behavior and broaden the general data base of no-bleed and low-bleed LO_2 propellant conditioning. Expanding the data base on LO_2 conditioning was intended to provide design guidelines to confirm the robustness of the feed duct design, particularly when applying a passive conditioning concept. The data base expansion included testing the limits of no-bleed and low-bleed conditioning with various configuration changes to the test facility and designed test article. The limits on propellant conditioning were defined by assessing when subcooled temperatures could no longer be obtained in the propellant feedline for each of the test configurations described below. As in the JIRAD, liquid nitrogen (LN_2) was used for testing rather that LO_2 for safety and operational concerns; however, it provides very similar fluid properties, heat fluxes, and flow velocities to that of LO_2.

TEST SEGMENTS

The test segments on the effects of no-bleed and low-bleed conditioning for this project were the following: (1) low velocity effects in the recirculation loop above the test article; (2) test article internal constriction impacts; (3) test article out-of-plane effects; (4) impact from an actual Titan LO_2 pump attachment; (5) feed duct slope effects; and (6) up-leg booster effects. The 15°-sloped test article was used for all segments except for the slope impact study which used the 0°-sloped article.

The low velocity segment was performed such that the lowest flowrate in the main feedline above the test article could be obtained while still maintaining subcooled temperatures within the test article. This segment was intended to be completed in one test day. The facility was limited by the fact that the range of low flowrates desired could only be measured with a 1-inch turbine flowmeter. Using a 1-inch flowmeter, however, allows measurement of only single-phase flow since two-phase flow through this type of meter threatens to damage the meter quite easily. After careful planning, it was agreed to circumvent the possibility of two-phase flow by taking a more direct route to fill the test article from the propellant trailer. With this more direct route, the circulation pump would be bypassed and liquid only would enter the test article. The longer path to the test article gave a higher probability of building up heat, which could consequently form vapor and transmit two-phase flow through the flowmeter, especially at lower flow rates.

The first attempt did not fulfill the low velocity test requirements satisfactorily, therefore, a repeat of this segment was performed. A reconfiguration of the facility was undertaken to prevent problems from recurring after the original attempt, i.e., circumventing saturated conditions from being reached in the cryogen before entering the test article. This reconfiguration involved flowing the cryogen through the main circulation pump while manipulating the valves in the main propellant feedlines. This procedure allowed the facility piping and test article to be properly chilled while avoiding two-phase flow through the 1-inch flowmeter. This approach to low velocity testing was simply underevaluated when discussing possibilities for the original attempt. Actual results for the low velocity segment, as well as other segments, will be presented later in the Results section.

The next segment was out-of-plane effects with the 15°-sloped test article. This test segment consisted of two separate test days. The first day consisted of turning the test article 30° clockwise out-of-plane. The second test day involved testing the 15° article 90° clockwise out-of-plane.

Constrictor effects on the no-bleed propellant conditioning concept comprised the third segment of this project. This segment also consisted of two separate test days. The first day involved testing with an 8-inch constrictor near the pump simulator of the article. This constrictor, which simulated a constriction effect from a LO_2 turbopump, was placed below the lower elbow of the 15° article. The second constrictor test day consisted of placing a 10-inch constrictor, which simulated a constriction effect that would be achieved from a flex joint, above the upper elbow of the 15° test article. Both the 8-inch and 10-inch constrictors were in place on the second test day.

The next test segment consisted of testing the no-bleed concept with real flight hardware. An Atlas-class Titan LO_2 pump was attached to the bottom of the test article in place of the usual pump simulator. Pump testing was then performed with the intent of simulating a constraint on a flight time-line after a tank prepressurization. Both no-bleed and low-bleed (0.96 gal/min) conditioning options were tested in this configuration. The facility run tank was started in a vented condition. The LN_2 propellant was circulated through the test article until steady-state conditions were reached. The run tank was then quickly pressurized to 22 lb/in^2 gauge while the pressure within the test article was adjusted to 107 lb/in^2 gauge. The pressures selected reflect actual values that would be applied to a flight vehicle during a prelaunch tank pressurization. After pressurization, the propellant was then circulated through the main feedline and test article until steady-state conditions were once again reached.

A 0°-sloped test article was employed to assess feedline slope effects during the next test segment. One test day was devoted to heat leak and one test day to propellant conditioning with this article.

The final segment to the LO_2 conditioning involved two days of up-leg booster testing with the 15° article. The sustainer and down-leg configurations were tested during the LO_2 propellant conditioning JIRAD.[1]

TEST MATRIX

As in the JIRAD, a design-of-experiments test matrix was built for each of the test segments. A total compilation of over 50 tests was performed for all the segments mentioned above. Table 1 summarizes the test parameters.

Table 1. Test configurations and parameters.

Segment	Bleed Rates (gal/min)	Heat Settings (Btu/h) Pump	Side	Velocity in Outer Loop (gal/min)	Pressure in Test Article (lb/in^2 gauge)	Test Duration (min)
Low Velocity	0.0, 0.96	3,000 5,500	2,500 4,500	30, 20, 10, 5	38	60
Out-of-Plane	0.0, 0.96	3,000 5,500	2,500 4,500	530	85	60
Constrictions	0.0, 0.96	3,000 5,500	2,500 4,500	530	85	60
LO_2 Pump Before Pre-Press	0.0, 0.96	xxxx xxxx	2,500 4,500	530	85	60
LO_2 Pump After Pre-Press	0.0, 0.96	xxxx xxxx	2,500 4,500	530	107	90
0° Slope	0.0, 0.96, 4.78	3,000 5,500	2,500 4,500	530	85	60
Up-Leg Booster	0.0, 0.96, 4.78	3,000 5,500 100 V*	2,500 4,500 100 V*	530, 350	85	60

* These heater settings (in volts) were the highest possible attainable and were employed to show similarity in performance between the up-leg booster configuration used in the NRA and the sustainer and down-leg booster configurations used in the JIRAD.

TEST FACILITY AND OPERATIONS

The test facility for this NRA had a similar set-up to the JIRAD project (fig. 3). As in the JIRAD, the test site was the hydrogen cold flow facility of the west test area (WTA) of MSFC. A 10,000-gal storage tank was used, which served as a reservoir for the LN_2. A 600-gal/min circulation pump was used to simulate velocity conditions across the top of the test article. Each test segment had its particular test article configuration, but the general facility remained the same from test to test. Silicon-diode temperature sensors were used for measuring the temperature profile within the feed duct except in the case of the 0° article, which used resistance temperature devices (RTD's). Si-diodes were originally chosen for temperature measurements because heat leak differences and flow difference disturbances caused by these sensors were deemed to be less than what would be caused by RTD's. This conjecture later proved to be unjustified as illustrated by using RTD's during the 0° article slope effects testing. (In terms of accuracy, RTD's measure temperature within ±0.1 °F while the Si-diodes measured within ±0.27 °F.)

During the first few tests of this project, it was discovered that one of the top two heaters of zone 1 (one of the pair of heaters above the upper test article elbow) was not transmitting heat because of a faulty connection within the heater. Having all power coming from one heater of the pair was thought to potentially cause asymmetries in the heat flow that would be detrimental to proper computational fluid dynamics (CFD) analysis. Therefore, it was decided to unhook both heaters in the faulty pair, provide the total heat needed in the zone through the other pair, then run a baseline heat leak check in this configuration. All test segments were subsequently run with the top two heaters unplugged for proper correlation with the heat leak data. It was later determined, however, that despite threats of asymmetries in heat flow, compensating for the total heat in zone 1 in the manner described versus providing the heat needed through the faulty heater pair would probably have had little effect on the outcome of the data.

A typical test day included a pretest and instrumentation checkout, approximately five tests, then a drain test to calibrate the Si-diode temperature sensors. The pretest would usually last for 1 to 2 h. A parametric test would last for about 1 h (the time it would usually take to reach steady state). Finally the drain test used about 1 1/2 h. A test day would therefore last an average of about 8 h.

As in the JIRAD, heat input to the feed duct was one of the most significant parameters to be tested. Therefore, baseline, ambient, and high heat load conditions were performed during preliminary heat leak checks on the 0° article and again on the 15° article (to repeat these results from the JIRAD) and on the separate Titan LO_2 pump section. Kapton heaters simulated heat loads present at the prevalve, flex joints, and pump simulator section of the articles. The Titan pump had no heaters attached. Heat leak from the test article was quantified by measuring the rate of gaseous nitrogen (GN_2) boiloff in actual cubic feet per minute with a gas flowmeter. The results from these calibration tests helped determine the heater settings for the heat load values in the test matrix. The calculated heat leak, $\dot{Q}$, is calculated with the following equation: $\dot{Q} = \rho \Delta \hat{H}_v \dot{V}$ where ρ is the density of the nitrogen boiloff based on temperature and pressure readings of the vapor, $\Delta \hat{H}_v$ is the latent heat of vaporization based on the nitrogen enthalpy change from liquid to gas, and $\dot{V}$ is the volumetric flowrate of the boiloff. $\dot{V}$ was taken from the gas flowmeter readings. Data from the thermophysical properties of nitrogen were also used to calculate the heat leak for all test article hardware. A sample calculation at ambient conditions for the Titan LO_2 pump heat leak follows:

Test article $P = 14.746$ lb/in^2 absolute

Vapor $P = 15.196$ lb/in^2 absolute

Vapor $T = 348$ °R

$$\rho = 0.1129 \text{ lb}_m/\text{ft}^3 ,$$

$$\Delta \hat{H}_v = 86.23 \text{ Btu/lb}_m ,$$

$$\dot{V} = 15.2 \text{ acfm} ,$$

$$\dot{Q} = 0.1129 l_m/\text{ft}^3 \times 86.23 \text{Btu/lb}_m \times 15.2 \text{ft}^3/\text{min} \times 60 \text{min/h} \cong 8\,879 \text{ Btu/h} .$$

Ambient heat leaks for all test articles and associated hardware are listed in the following:

Test Hardware	Ambient Heat Leak (Btu/h)
Titan LO_2 Pump	8,879
Pump Simulator	1,400
Entire 15° Test Article	2,989
Entire 0° Test Article	2,350

Six skin temperature thermocouples were attached to the outside of the LO_2 pump. One RTD was attached to the outlet of the pump and one Si-diode was attached to the bottom of the feedline reducer near the inlet of the pump. The RTD used for the LO_2 pump was used during other tests near the top of the test article. The Si-diode sensor used in the pump was one which was normally placed in the top of the pump simulator in other test segments.

As in the JIRAD, it was necessary to calibrate the Si-diode sensors at the end of each test day because of the lack of consistency of the performance of the diodes. For each test day, a correction factor was applied to the temperature data to assure proper Si-diode readings. The correction factor was determined by first filling the test article then monitoring the temperature in the feed duct as propellant was drained from the duct at a consistent low flow rate of 3 gal/min. Upon first draining the article, the pressure in the feed duct was set at 30 lb/in^2 gauge with the propellant at the corresponding saturation temperature. As the liquid level decreased, the pressure decayed. The saturation temperature was always established by the current pressure according to the tables on the thermophysical properties of nitrogen. Subcooled temperatures can change the correction factor as can a drastic change in the drain flow rate. Time versus temperature data were assessed to reveal when a temperature sensor was no longer immersed in liquid. Before a probe uncovered, it was surrounded by liquid at a slightly higher temperature and pressure than the saturated liquid at its surface. After a probe uncovered, it was surrounded by superheated vapor, which was warmer than the saturation temperature. Therefore, the time versus temperature data for each diode showed a minimum in the curve after a sensor went dry. The temperature difference between the saturation temperature (determined from the saturation pressure and the thermophysical properties of nitrogen) and the minimum value on a sensor's time versus temperature curve were used as the correction factor for that test day's sensor reading. Additionally, a delta pressure sensor was used to track the liquid level within the test article. Liquid level detection by the delta pressure sensor was useful in verifying when each Si-diode sensor uncovered.[3] Figure 4 shows an example of a time versus temperature plot used to determine a Si-diode's correction factor. RTD's were also shown to have correction factors but at smaller values than for Si-diodes.

RESULTS

Subcooled temperatures were obtained in the feedline for all conditioning concepts except for velocity rates below 28 gal/min. Subcooled temperatures were not obtained in the Titan LO_2 pump before prepress conditions were applied. However, vapor entrainment within the LO_2 pump was not a concern since net positive suction pressure (NPSP) requirements do not have to be met in the pump itself.[4] The facility pressure was established at 85 lb/in^2 gauge for all segments except for low velocity which was conducted at 38 lb/in^2 gauge. From consulting thermophysical nitrogen data, the saturation temperature at 85 lb/in^2 gauge is about 177 °R. With the exception of the lowest range of velocity tests, subcooled temperatures of 150 °R and below were consistently seen within the feedline and pump simulator at the established facility pressure of 85 lb/in^2 gauge for all test segments. Figures 5 to 10 show examples of temperature profiles established throughout the feedline for the 30° and 90° out-of-plane effects, 8-in and 10-in constrictor effects, 0°-slope effect, and up-leg booster effect studies.

At 38 lb/in^2 gauge, which was the facility pressure established for low velocity, the saturation temperature is about 162 °R. Figures 11 to 13 illustrate the temperature versus time plots based on temperature probes in the top and middle of the feedline and in the pump for 30-, 20-, and 10-gal/min outer flow loop velocity rates. (The 5-gal/min flowrate listed in the matrix section was not attempted.) Temperatures established for the flowrate of 30 gal/min started at 154 °R and decreased to a fairly steady temperature of 150 °R. The 30-gal/min test actually varied in flowrate somewhat, and the lowest flowrate established during this test was determined to be 28 gal/min. The 20-gal/min test had temperatures creeping upward from just under 151 °R. For even lower flowrates (attempted at 10 gal/min), the temperature tended to rise more sharply; the first attempt at a 10-gal/min flowrate showed a rise in temperature, then a decrease, the latter probably due to refilling the test article. For flowrates below 20 gal/min, it was determined that saturation temperatures were already reached within the feed duct even before conditioning was begun. Figure 14 illustrates the temperature profiles for different low-velocity flowrates. Temperature sensors before the feedline indicated that saturated temperatures were being obtained even before entering the feed duct for flowrates of 20 gal/min and lower. Because of facility limitations prohibiting proper flows to be obtained through the 1-in flowmeter, the lowest velocity rate attainable below 28 gal/min remains unknown. Even with the second low-velocity test attempt, two-phase flow again proved a great hardship on the 1-in flowmeter. The 1-in meter was the only flowmeter available, however, to measure within the range of velocities desired.

Conditioning studies using the Titan LO_2 pump conducted before the prepressurization studies showed that saturated conditions were being obtained in the pump but not the feedline. The saturated conditions in this case have been attributed to vapor pockets forming in the irregularly shaped pump. Vapor forming in the pump was actually not a concern since NPSP requirements do not actually have to be met in the pump itself. However, the Titan LO_2 pump prepressurization simulation proved successful for maintaining subcooled temperatures both in the feedline and the pump for at least 30 min when pressurizing the test article to 107 lb/in^2 gauge. Figure 15 shows temperature versus time results for the Titan LO_2 pump before prepressurization conditions, and figure 16 shows a temperature versus time plot for a prepressurization situation using results from the skin temperature and RTD probes in the pump. For a prepressurization situation, after temperatures in the test article reached steady state (while testing with the run tank in a vented condition and the test article pressurized to 85 lb/in^2 gauge for 2,000 s), the run tank was pressurized quickly to 22 lb/in^2 gauge and the test article pressure adjusted to 107 lb/in^2 gauge. At 107 lb/in^2 gauge the saturation temperature is 182 °R. Subcooled temperatures below 170 °R were seen in the pump for more than one-half hour after pressurization. Of all tests performed during phase A, simulating a Titan LO_2 pump prepress situation may be considered the best demonstration of the effects on propellant conditioning during an actual flight timeline because of the authentic flight hardware used in this segment to prove the concept of no-bleed feasibility. Figures 17 and 18 also compare temperature profiles within the feedline before and after prepress conditions.

For a more detailed discussion on the analysis and results of the data obtained from this project, please see reference 4. All data from this testing may be found on the MSFC Sun work station system.

CONCLUSION AND FUTURE WORK

Most of the limits tested in this project proved that subcooled temperatures could be maintained in the feed duct. The success of obtaining subcooled temperatures for both no-bleed and low-bleed concepts for the limits tested illustrates the robust design of the feed duct applied. The data base on design guidelines has been deemed to be about 90-percent complete. Future work will include further verification of the low-velocity limits on no-bleed. Actual LO_2 verification is also expected to be pursued under future projects at the oxygen cold flow facility, which was completed in March 1995 in the WTA of MSFC.

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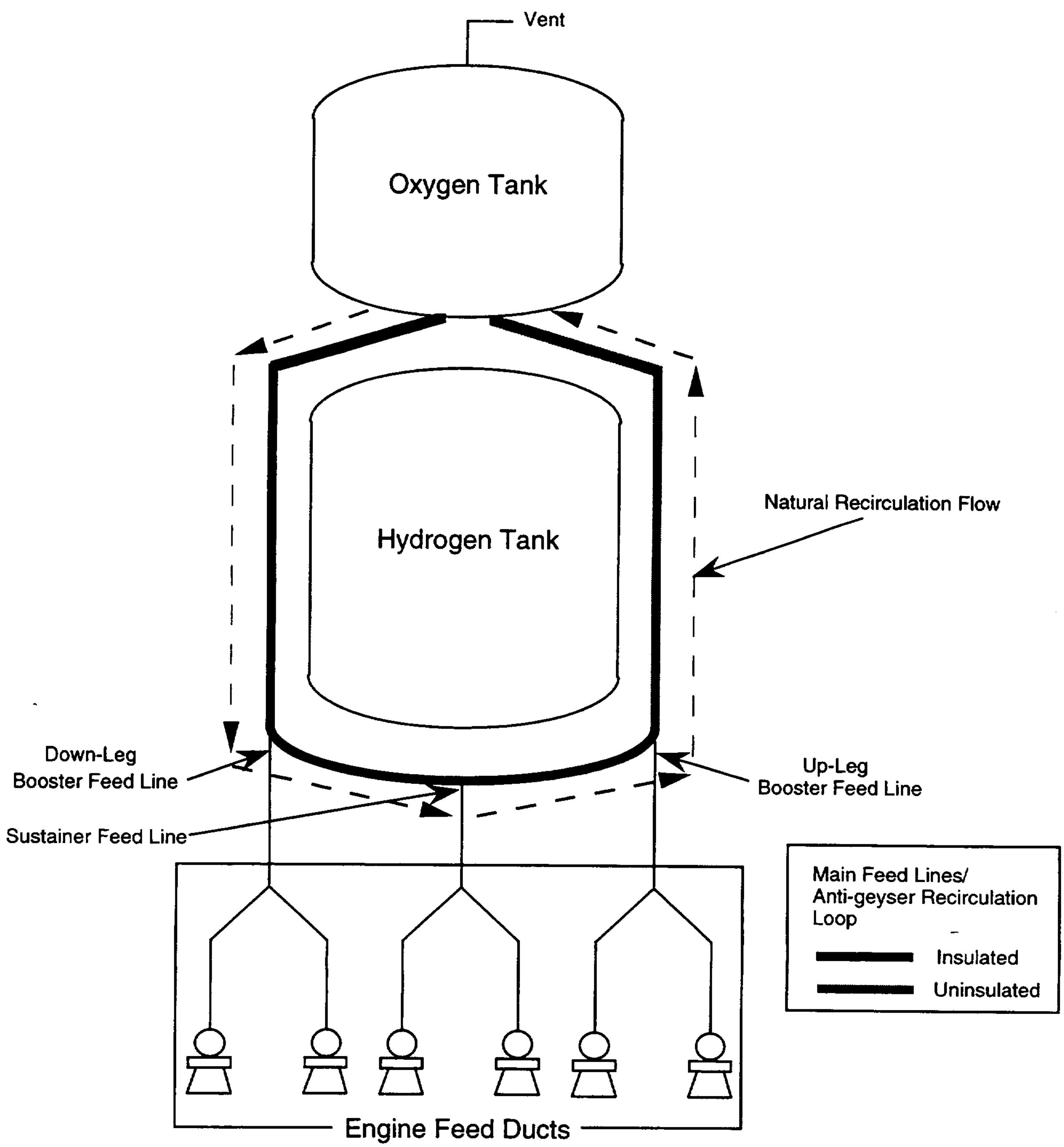

Figure 1. Diagram of a heavy lift launch vehicle, main propulsion system.

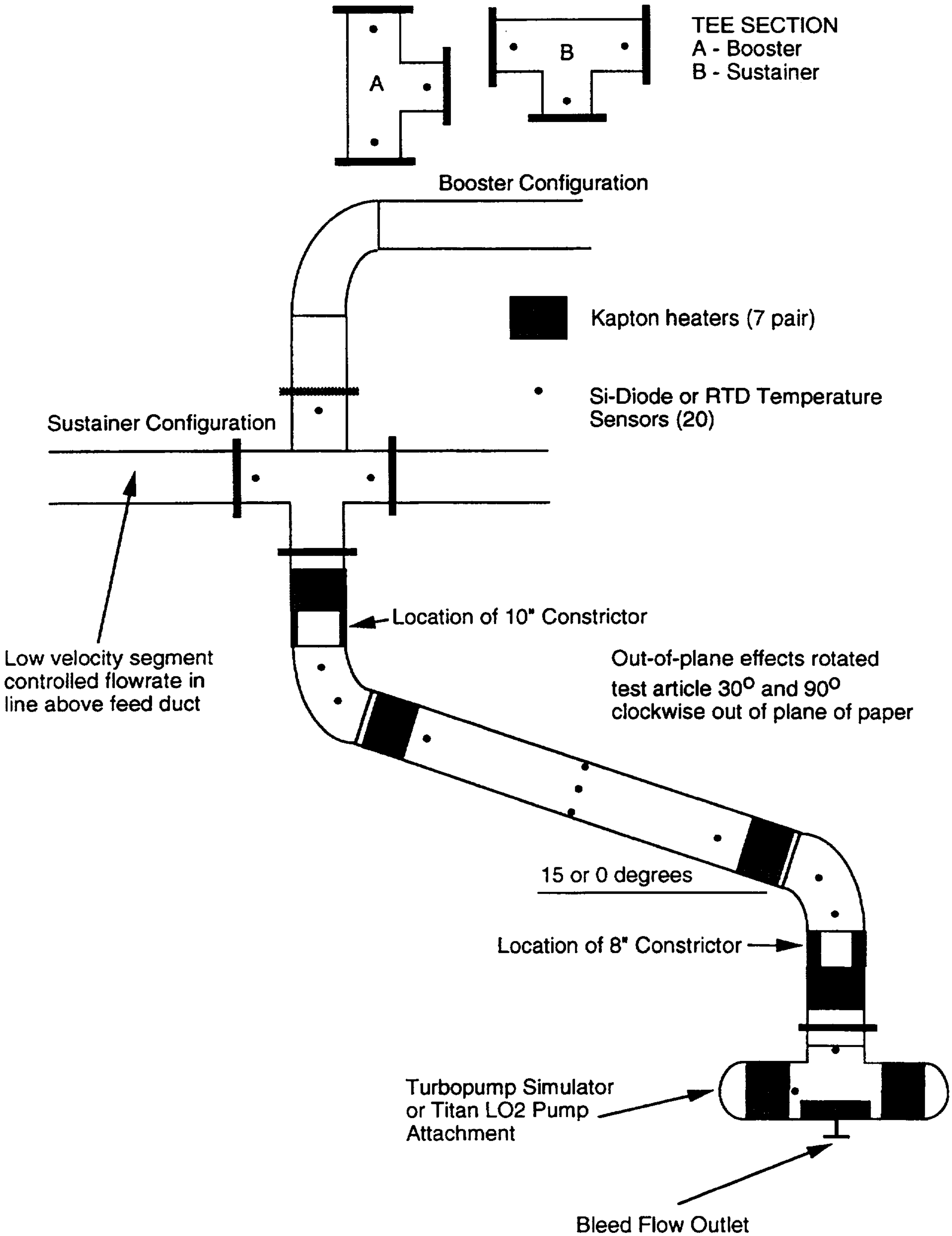

Figure 2. Detailed drawing of the test article(s) used in the LO_2 propellant conditioning project. Each article was constructed of 6061 12-in inside diameter aluminum with a 0.375-in wall.

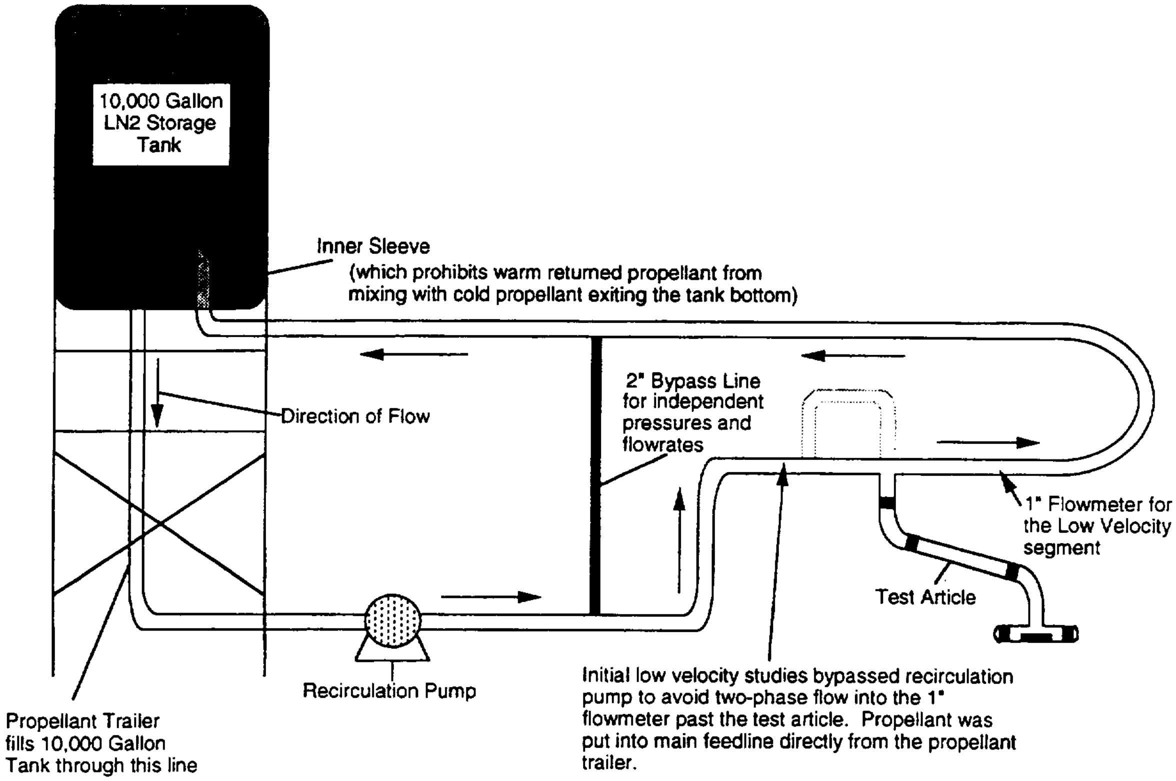

Figure 3. General test schematic for the LO_2 propellant conditioning project at the liquid hydrogen cold flow facility in the WTA of MSFC.

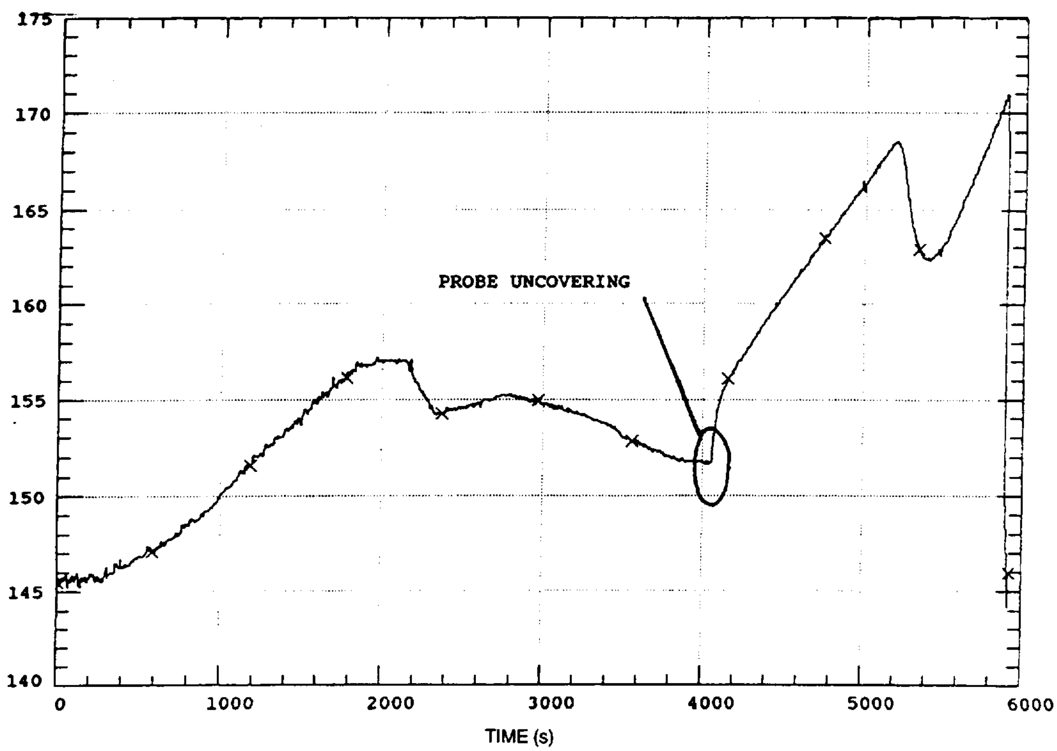

Figure 4. Si-diode temperature versus time calibration curve.

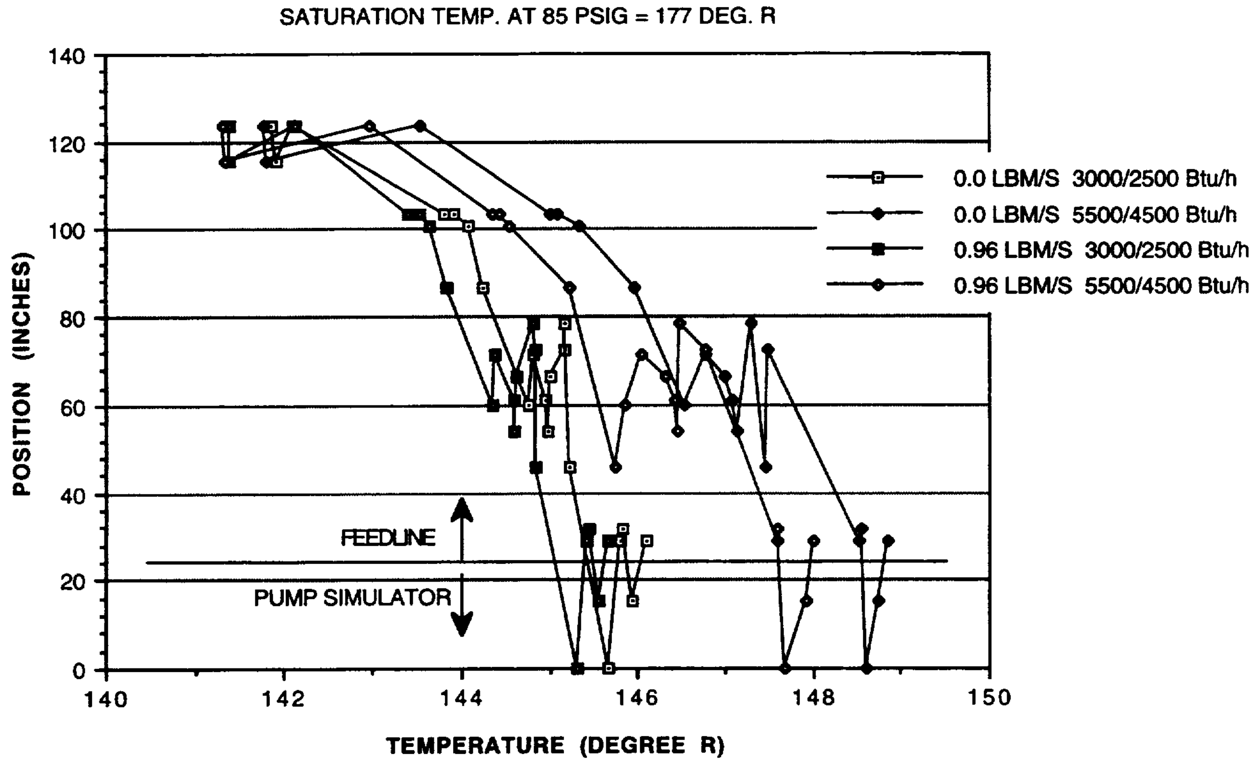

Figure 5. 30° out-of-plane temperature profiles, 15° test article.

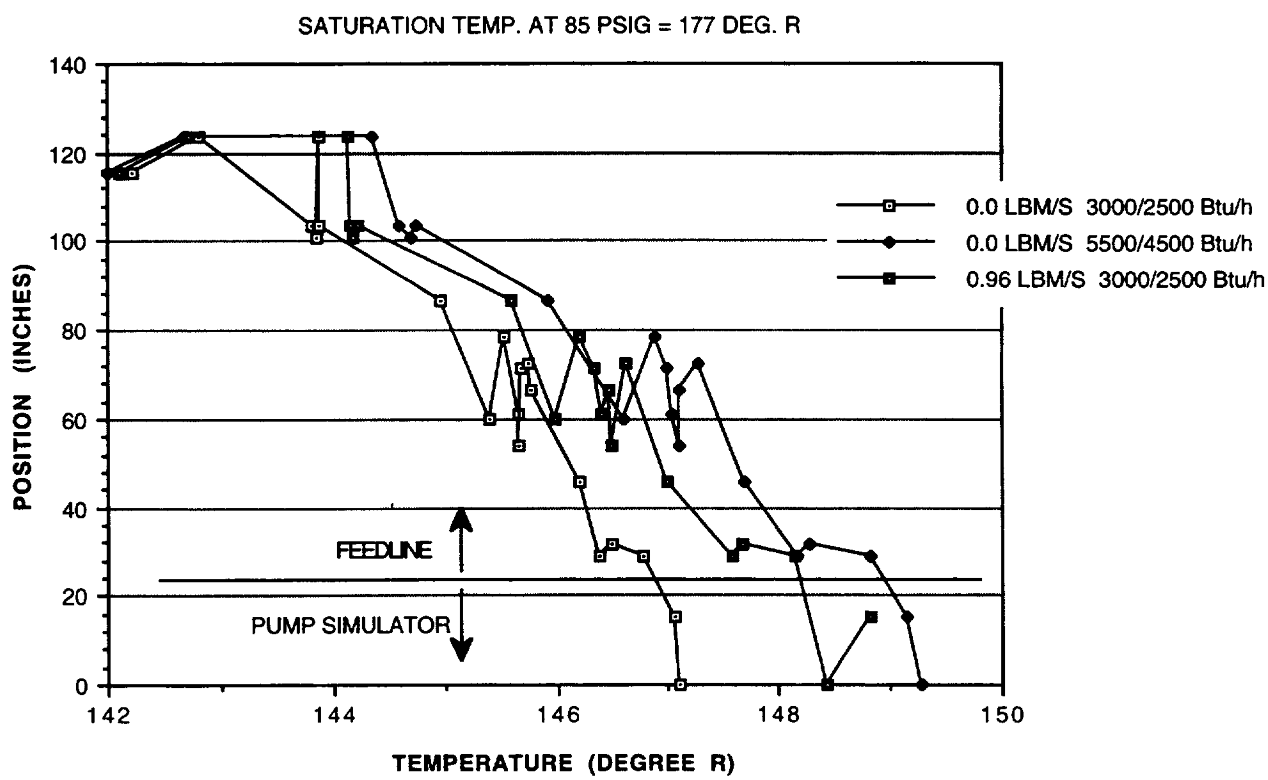

Figure 6. 90° out-of-plane temperature profiles, 15° test article.

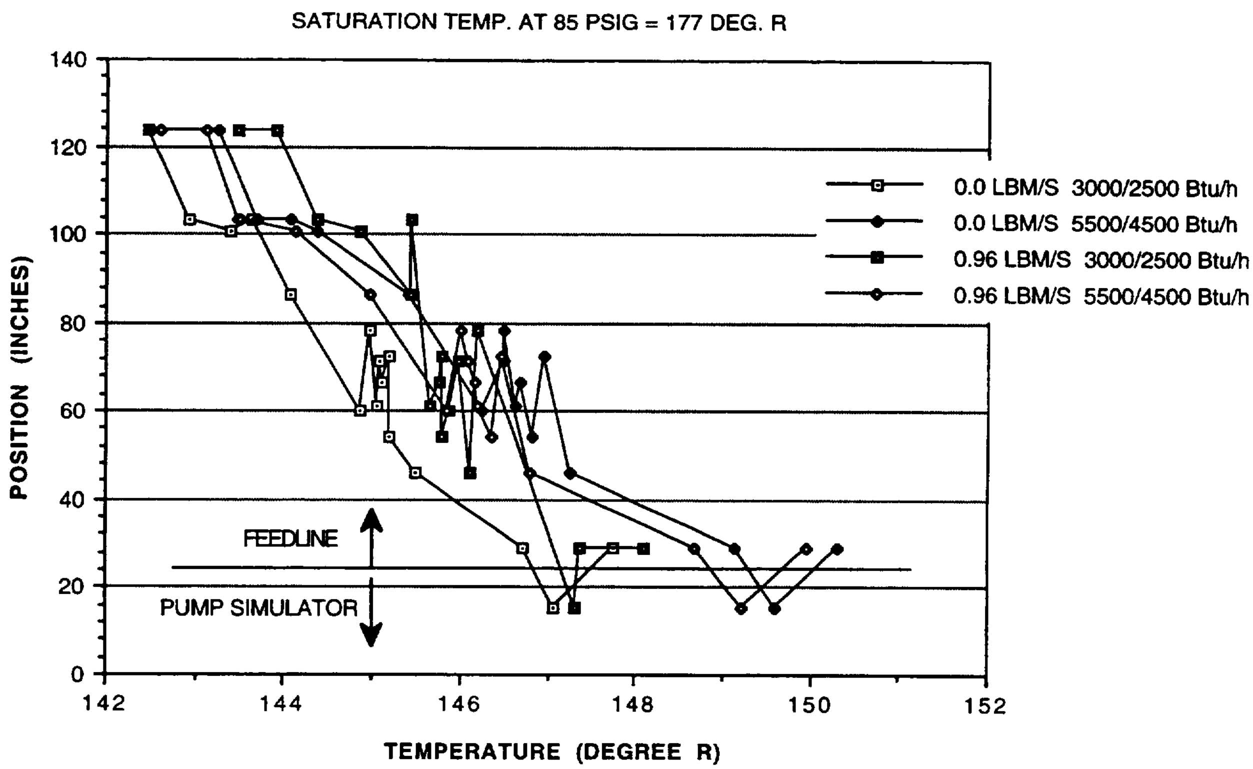

Figure 7. 8-inch constrictor temperature profiles, 15° test article.

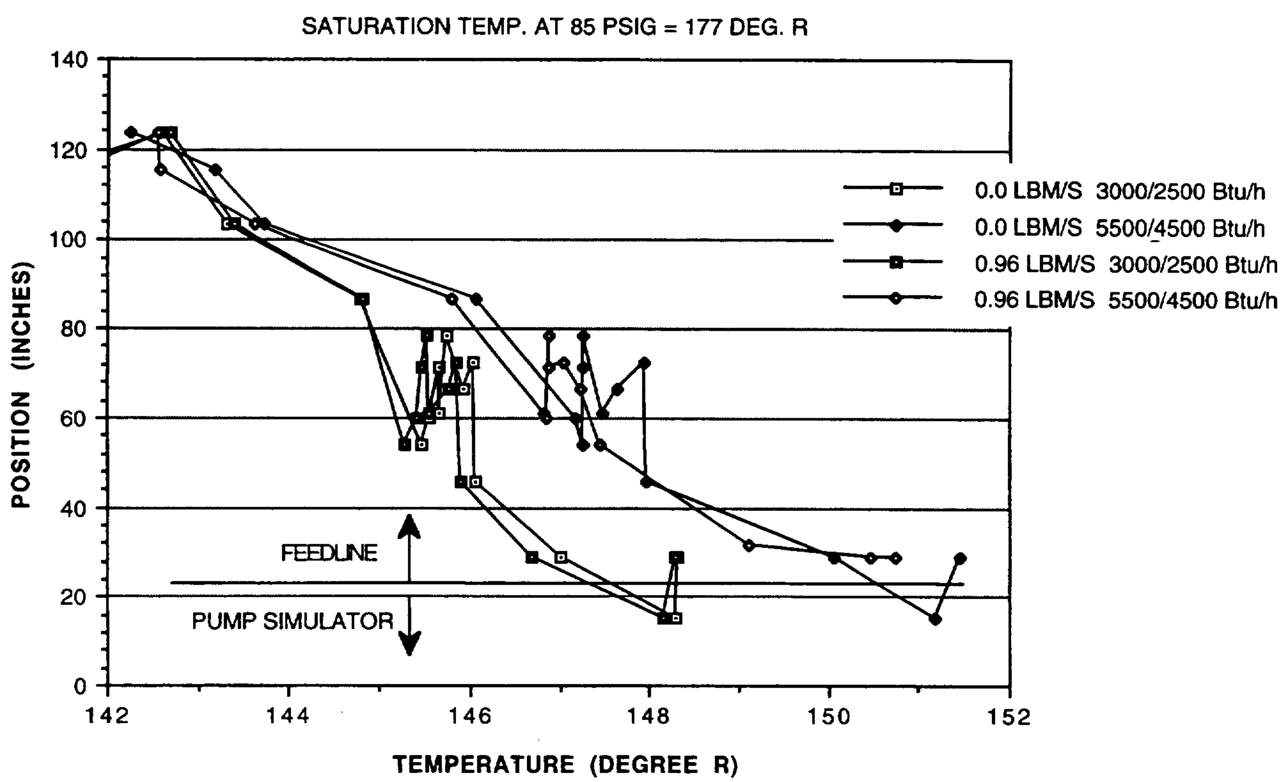

Figure 8. 8- and 10-inch constrictor temperature profiles, 15° test article.

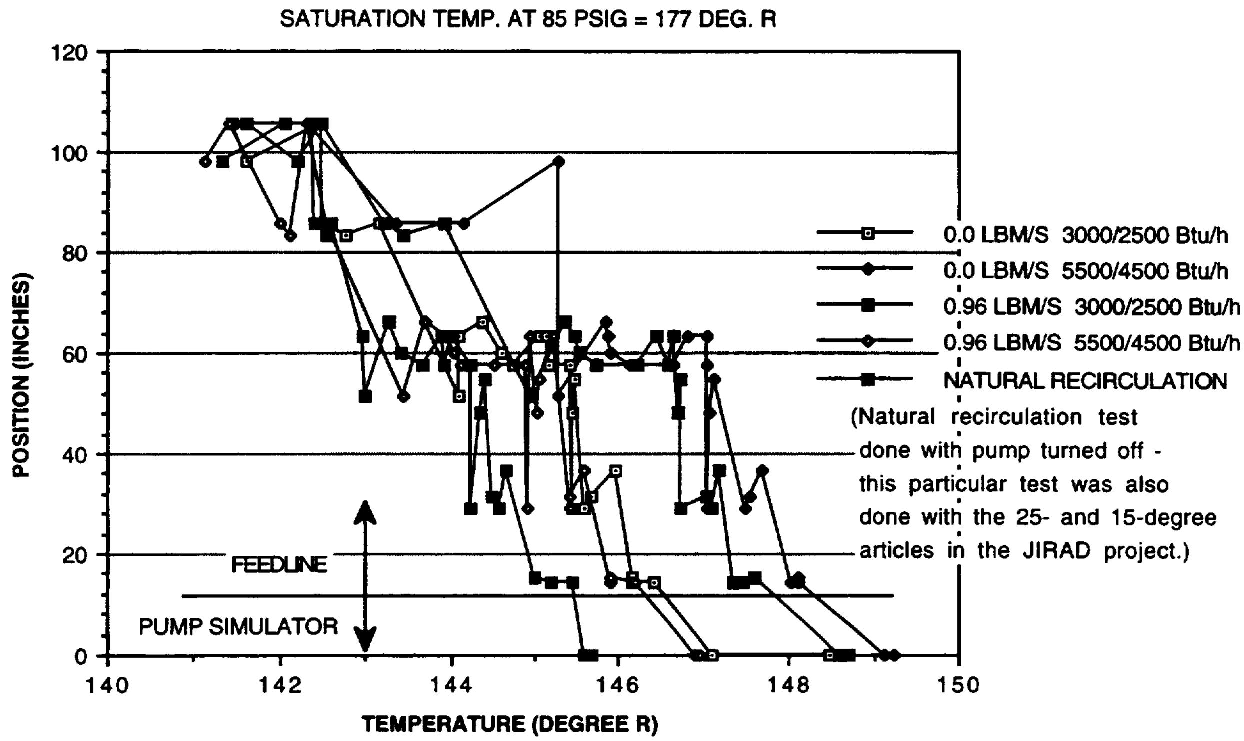

Figure 9. 0° slope temperature profiles, 0° test article.

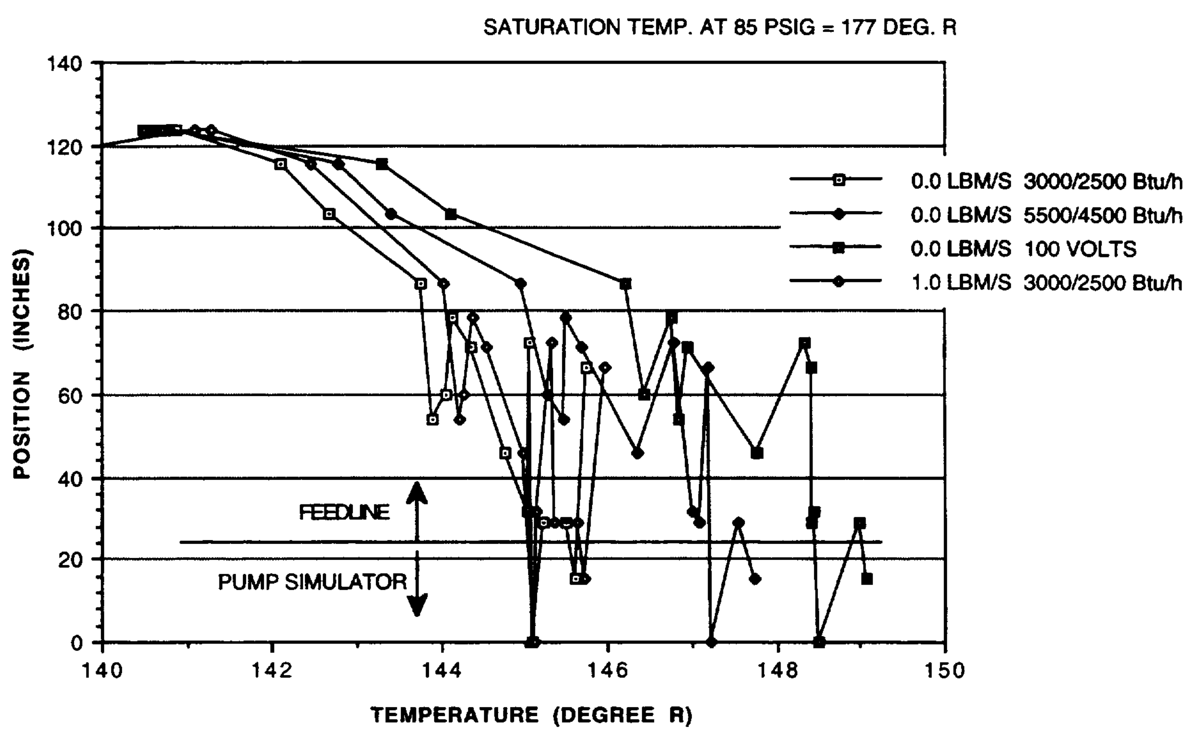

Figure 10. Up-leg booster temperature profiles, 15° test article.

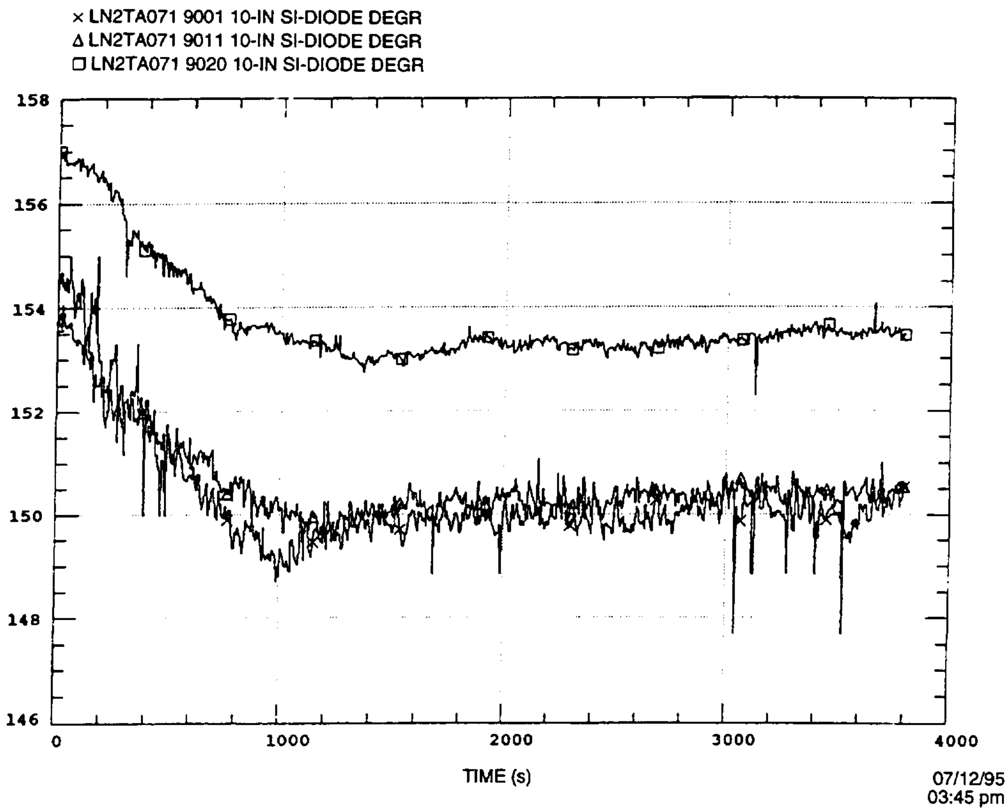

Figure 11. Temperature versus time plot for 30-gal/min low-velocity study.

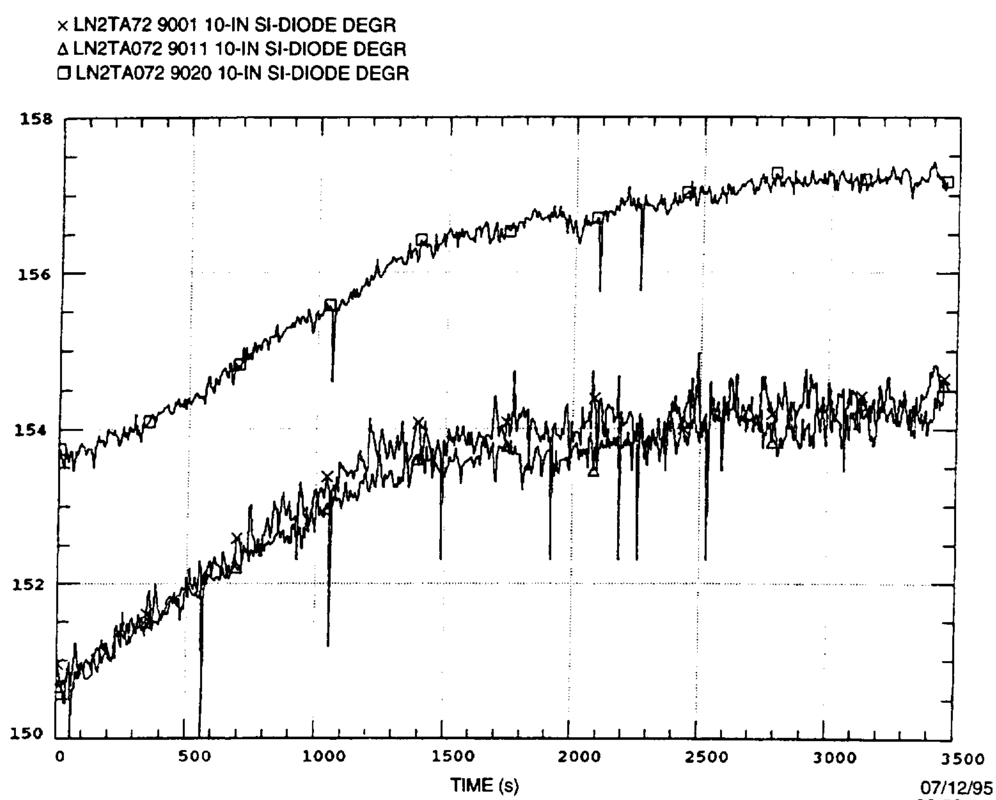

Figure 12. Temperature versus time plot for 20-gal/min low-velocity study.

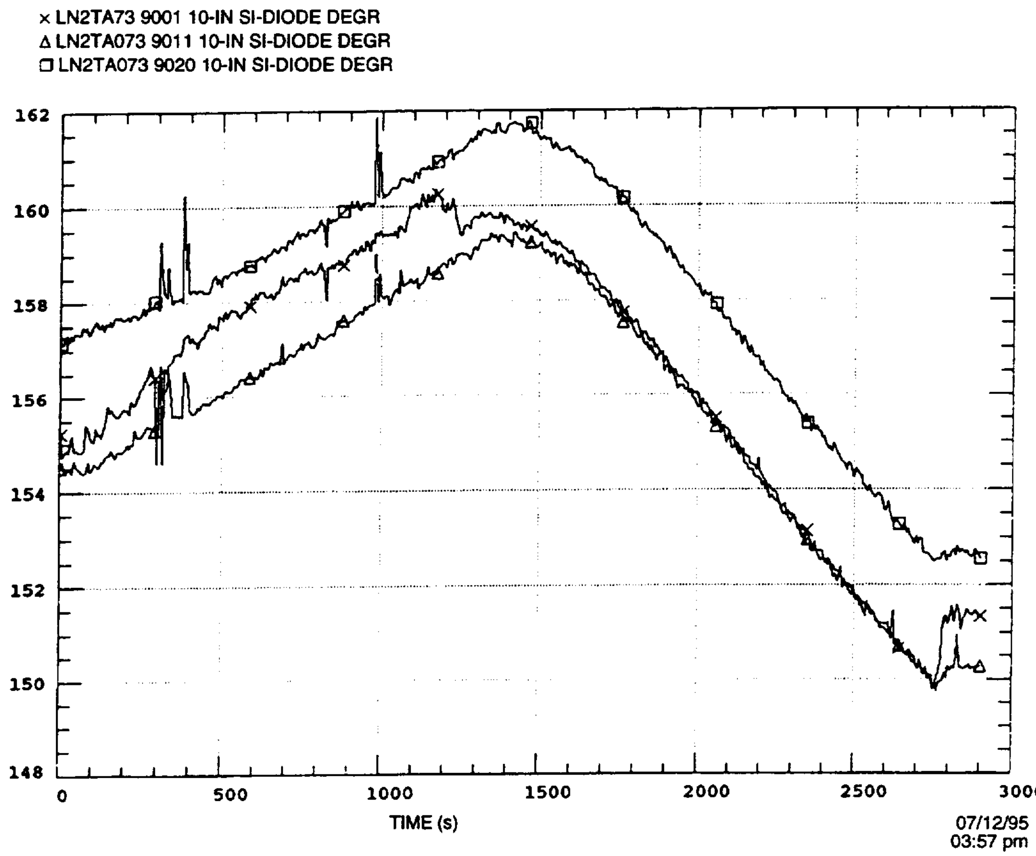

Figure 13. Temperature versus time plot for 10-gal/min low-velocity study.

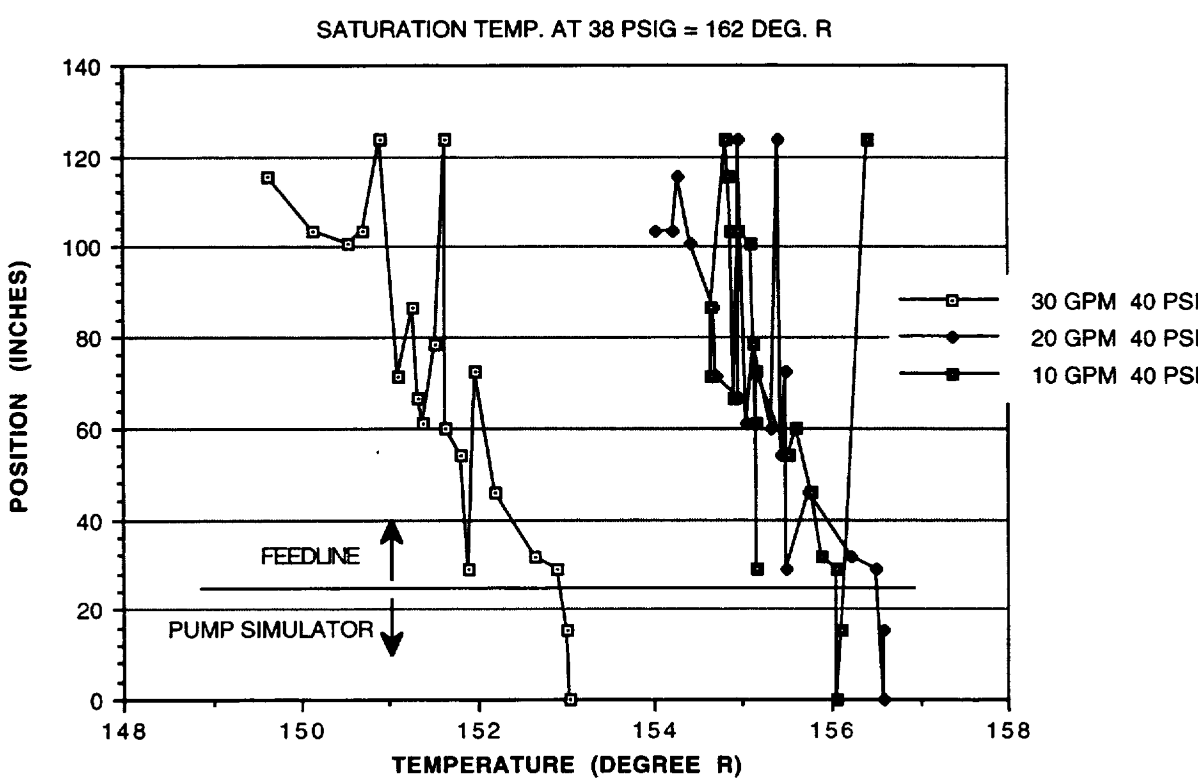

Figure 14. 30-, 20-, and 10-gal/min low-velocity temperature profiles, 15° test article.

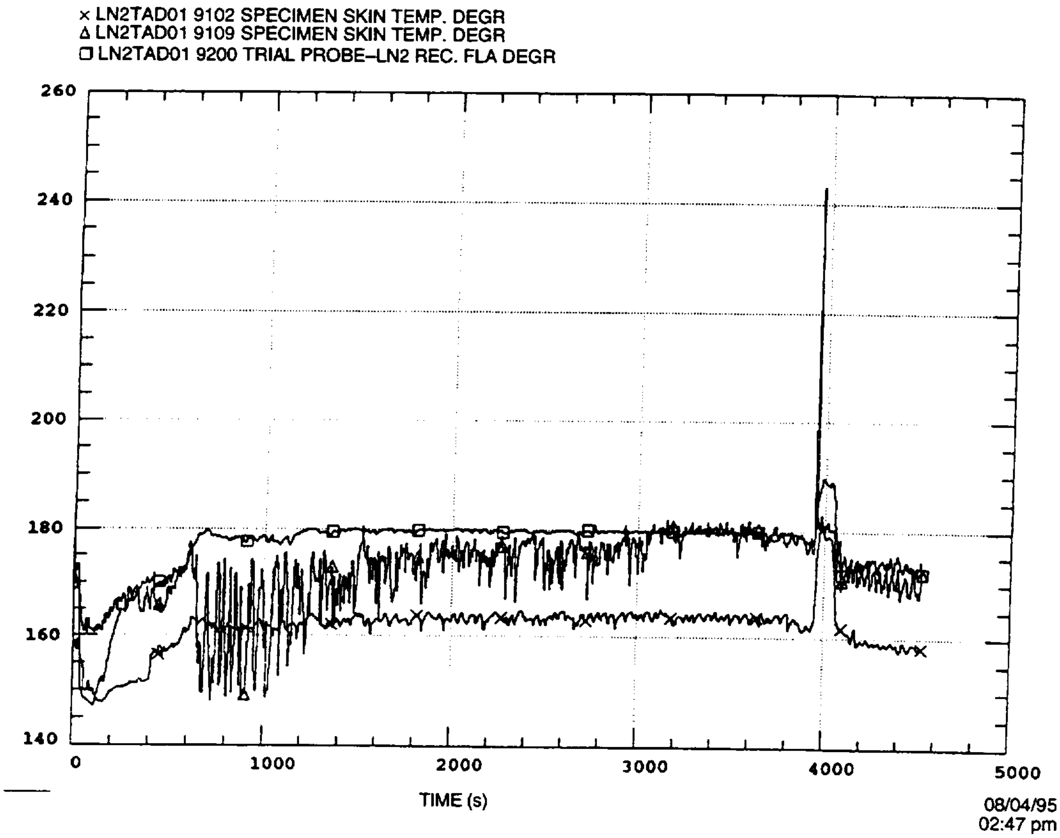

Figure 15. Temperature versus time plot for probes in pump before prepress.

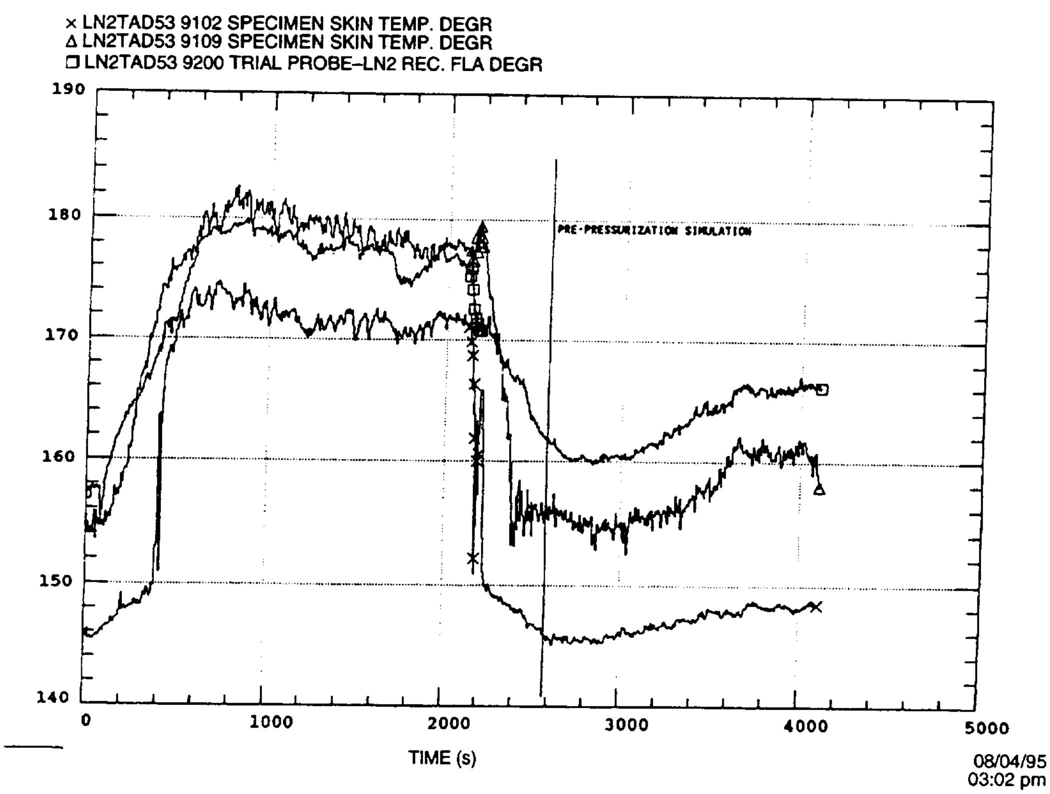

Figure 16. Temperature versus time plot for probes in pump after prepress.

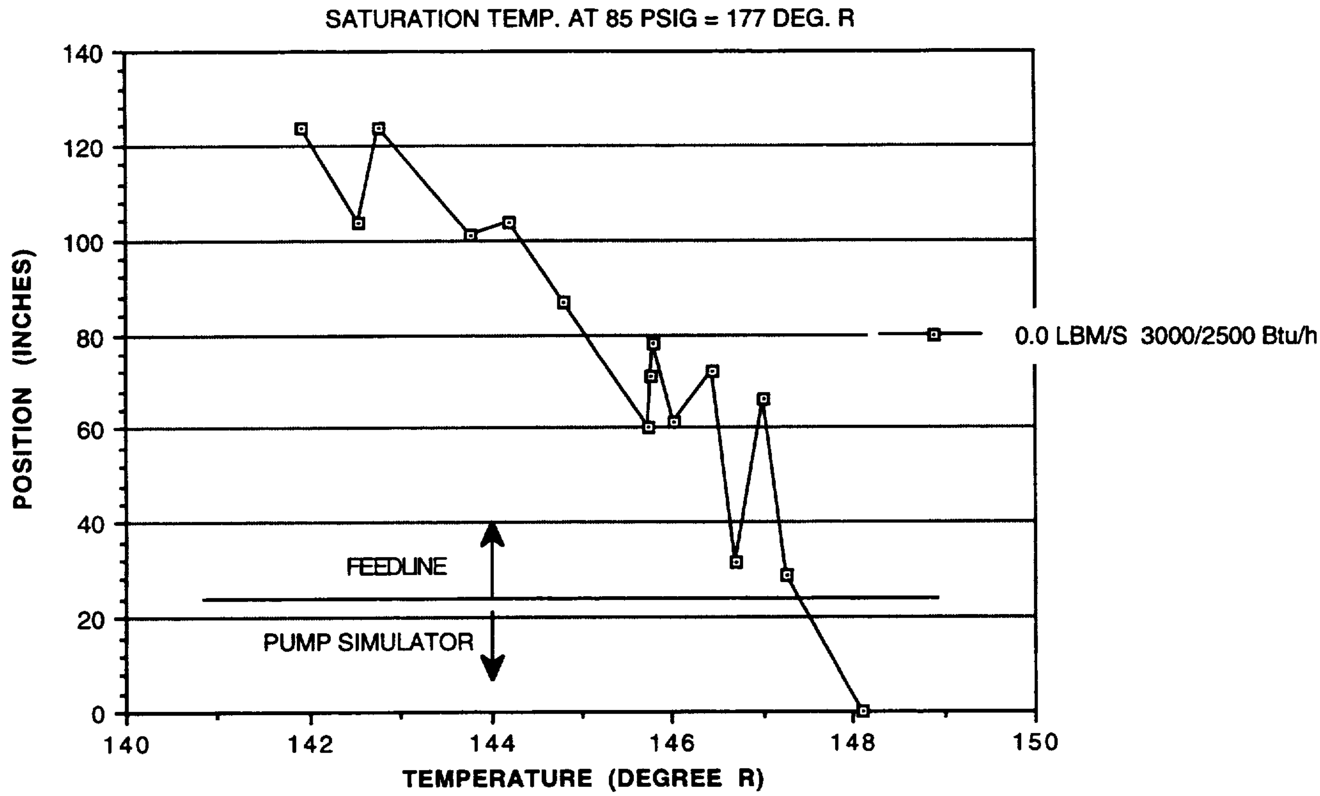

Figure 17. Temperature profiles in feedline before prepress.

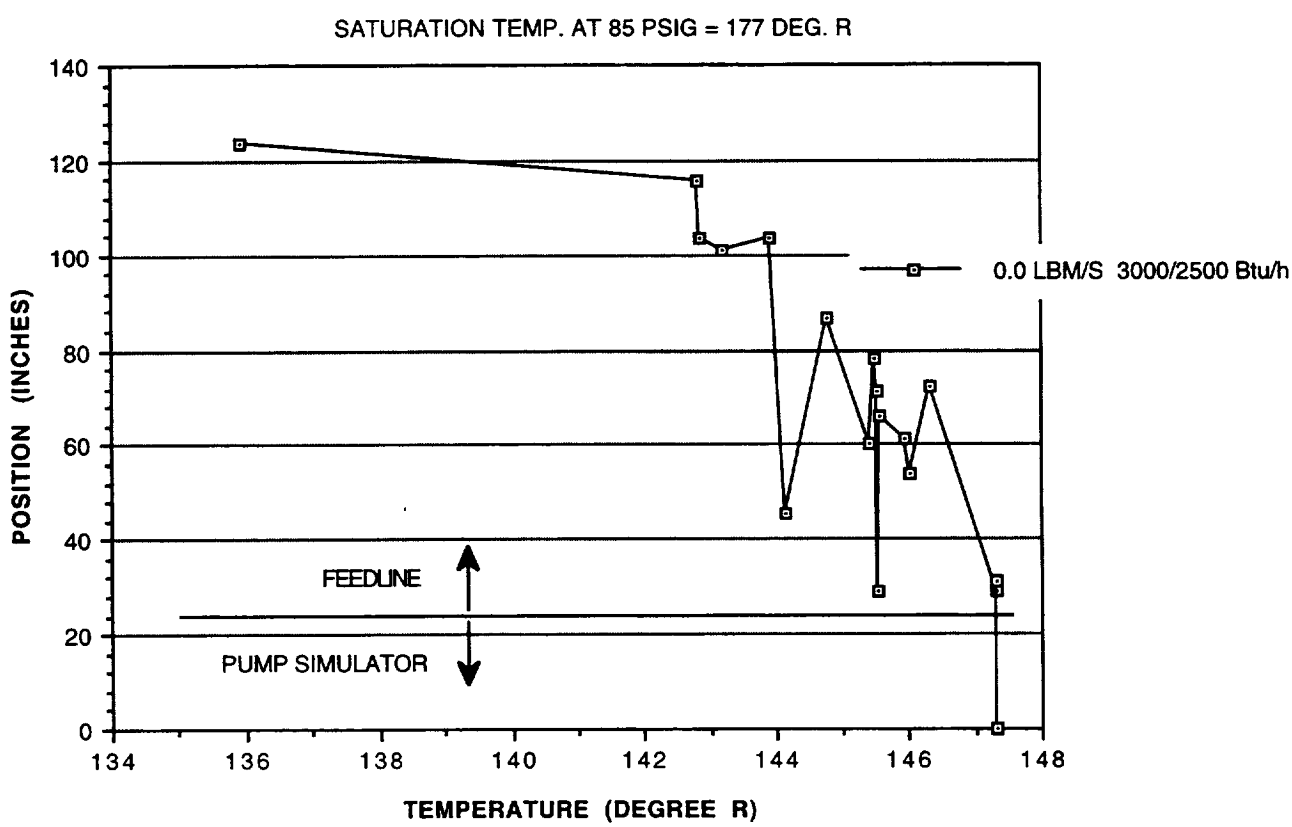

Figure 18. Temperature profiles in feedline after prepress.

APPROVAL

ADVANCED LIQUID OXYGEN PROPELLANT CONDITIONING CONCEPT TESTING II

By G.L.E. Perry, G.K. Mehta, and J.H. Hastings

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

for

J.M. MCMILLION
Acting Director, Propulsion Laboratory

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13. ABSTRACT *(Maximum 200 words)*

More extensive testing was performed through a NASA research announcement (NRA) between Marshall Space Flight Center (MSFC) and Lockheed Martin Astronautics on the promising LO2 propellant conditioning concept of passive recirculation (no-bleed). Data from the project is being used to further anchor models in LO2 conditioning behavior and broaden the data base of no-bleed and low-bleed conditioning. Data base expansion includes results from testing the limits of no-bleed and low-bleed conditioning with various configuration changes to the test facility and designed test article. Configuration changes include low velocity effects in the recirculation loop above the test article, test article internal constriction impacts, test article out-of-plane effects, impact from an actual Titan LO2 pump attachment, feed duct slope effects, and up-leg booster effects. LN2 was used as the test fluid. The testing was conducted between July 1994 and January 1995 at the west test area of MSFC. Data have shown that in most cases passive recirculation was demonstrated when the aforementioned limits were applied.

14. SUBJECT TERMS

feed duct, feedline, liquid oxygen (LO2), no-bleed, passive recirculation, propellant conditioning

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